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Dynamic Electrotactile Adjustment of Perceived Area via Transcutaneous Interferential Electrical Stimulation

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I. Introduction

An electrotactile display, which creates tactile sensations via electrical stimulation, has gained considerable attention in fields such as biomedical engineering and computer science [1]. Among the various methods, Transcutaneous Electrical Stimulation (TES) is widely adopted for its non-invasive nature. However, TES faces a critical challenge: adjusting the perceived area without physical reconfiguration of electrodes [2] or modulating current intensity [3]. Physical electrode adjustments restrict dynamic control, while modulating current intensity is complicated by the skin impedance and the stimulus-perception relationship.

To address these limitations, this study proposes Transcutaneous Interferential Electrical Stimulation (TIES), a novel variant of TES that uses sinusoidal waves with different frequencies to produce interference patterns within tissue. This principle has been successfully applied in muscle stimulation [4] and brain stimulation [5]. By controlling these interference patterns, TIES offers a flexible approach to adjust the perceived area without changing electrode configuration or current intensity.

While Lim et al. experimentally demonstrated that interference sine waves can produce tactile sensations via electrical stimulation [6], their study did not investigate whether this approach could effectively adjust the perceived area. This capability remains unclear and is the focus of our investigation. In this paper, we present preliminary results from a computational model that examines how TIES interacts with axons of different orientations. Through this approach, we characterize the neural activation patterns under varying stimulation parameters, providing theoretical foundations for adjusting the perceived area in an electrotactile display.

II. Computational Modeling

Electrotactile feedback involves two interconnected phenomena: the electrical potential distribution and the subsequent neural activation. When applied to the skin, TES creates potential differences that generate ionic currents. These currents induce electrical potential gradients along sensory nerve axons, which can trigger action potentials and create tactile sensations [3].

The human fingertip contains diverse sensory nerves with varying orientations and spatial distributions: Aβ fibers for tactile sensation, while Aδ and C fibers for temperature and pain. This diversity is significant as field characteristics determine both which axons activate and their perceived area. TIES creates interference patterns within tissue and these patterns generate spatially and directionally varying fields that could selectively activate specific neural populations based on orientation. Our computational model explores how these interference patterns can simultaneously adjust the perceived area and type of tactile sensations. This approach provides insights into TIES mechanisms before conducting user studies.

A. Methods

To investigate the neural mechanisms of TIES, we constructed a multi-physics simulation framework combining: the finite element method (FEM) for evaluating electrical fields generated by TIES and numerical analysis of the Hodgkin–Huxley (HH) model to evaluate neural activation. The simulation workflow consisted of two sequential components:

First, FEM was used to calculate the spatial and temporal distribution of electrical potentials throughout a simplified fingertip model as shown in Fig. 1(a). Tissue electrical properties were implemented as frequency-dependent values based on published data.

Second, the potential distribution $V(r,t)$ along the axons served as extracellular potentials $\Psi(r,t)$ in our neural dynamics simulation, where r denotes the direction of the axon. We focused on axons connected to mechanoreceptors located approximately 1 mm below the skin surface, examining both horizontally-oriented somatosensory nerve fibers (associated with Merkel cells for pressure sensation) and vertically-oriented somatosensory nerve fibers (associated with Meissner corpuscles for vibration sensation) [3]. HH model simulated membrane dynamics in response to these extracellular potential gradients, determining whether and where action potentials would occur. For physiological relevance, neural activation was determined when: depolarization occurred at a position along the axon, and this depolarization propagated to the endpoints (0.0 or 1.0).

Table I summarizes the four stimulation conditions examined to evaluate TIES's capabilities: conventional TES (*Stim-A*) serving as baseline, and three TIES variants with different beat frequencies (*Stim-B*, *Stim-C*, and *Stim-D*). Current intensity remained constant at 0.5 mA per electrode across all conditions to isolate the effects of stimulation patterns from amplitude differences.

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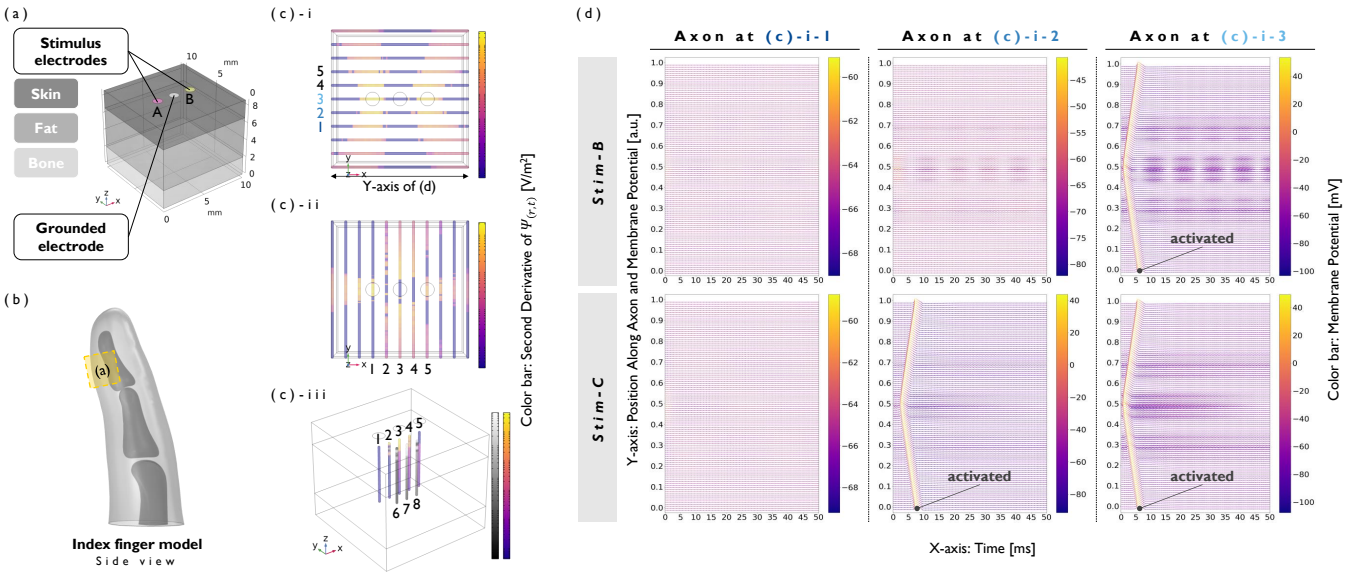

Fig. 1. Simulation model and its results: (a) Three-layered simplified fingertip model consisting of skin (2.0 mm), fat (4.6 mm), and bone (2.1 mm). (b) The yellow area indicates the anatomical location of the model shown in (a). (c) FEM simulation results for the activation function, with axons at 1 mm intervals. (d) Comparative neural activation from different stimulation patterns, with *Stim-B* and *Stim-C* presented as representative examples.

TABLE I
FOUR STIMULUS PATTERNS

Patterns	Waveform	Frequency$_1$ †	Frequency$_2$ †
Stim-A	pulse, monophasic	100 Hz	100 Hz
Stim-B	sine, differential	2000 Hz	2100 Hz
Stim-C	sine, differential	2000 Hz	2010 Hz
Stim-D	sine, differential	2000 Hz	2000 Hz

Note *Stim-A*: 200 µs pulse width, *Stim-B–D*: 100/10/0 Hz beat freq.
† f_1 from the electrode A, f_2 from the electrode B in Fig. 1(a).

B. Results and Discussion

Table II summarizes neural activation patterns across four stimulation conditions associated with Table I. In an XY-plane, *Stim-B* activated only the axon at position 3 along the X-axis, while *Stim-C* activated nearly the same number of axons as *Stim-A*. Along the Z-axis, *Stim-B* activated axons at fewer positions (only positions 3 and 7) than *Stim-A*. These highlight TIES's capability to focus stimulation on axons connected to Merkel cells and Meissner corpuscles compared to TES.

Stim-D activated axons similarly to *Stim-B*, contradicting [5], which reported no stimulation with identical-frequency sine waves in both channels. This discrepancy may stem from differences in electrode configurations and axonal conductivity/permittivity settings, warranting further investigation into spatial arrangement effects on TIES efficacy.

III. CONCLUSION

Our simulation study shows that TIES has potential to dynamically adjust the number of activated axons. This approach offers a basis for developing a high-resolution electrotactile display with enhanced adjustment over both spatial and qualitative aspects of tactile feedback.

TABLE II
NEURAL ACTIVATION UNDER FOUR STIMULUS PATTERNS

Axonal Orientation	Position	*Stim-A* (TES)	*Stim-B* (TIES)	*Stim-C* (TIES)	*Stim-D* (TIES)
Fig. 1(c)-i X-axis	1	○	○	○	○
	2	●	○	●	○
	3	●	●	●	●
	4	●†	○†	●†	○†
	5	○†	○†	○†	○†
Fig. 1(c)-ii Y-axis	1	○	○	○	○
	2	○	○	○	○
	3	●	○	●	○
	4	○†	○	○	○†
	5	○†	○	○	○†
Fig. 1(c)-iii Z-axis	1	○	○	●	○
	2	●	○	●	○
	3	●	●	●	●
	4	●†	○	●	○†
	5	○†	○	○	○†
	6	○	○	○	○
	7	●	●	●	●
	8	○†	○	○	○†

Note ●: Activated, ○: Inactivated.
† Not simulated; determined by model symmetry.

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